

# Performance of dynamic and ambiguity-fixed GNSS-derived LEO orbits in SLR validation and network calibration

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# Motivation

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- Numerous geodetic satellites are in low Earth orbit (LEO)
- Precise orbit determination (POD) by GNSS (GPS), some tracked by Satellite Laser Ranging (SLR)
- GNSS-based LEO POD has witnessed remarkable quality improvements in recent past (e.g., more accurate modeling of gravitational and non-gravitational forces, single-receiver ambiguity fixing, ...)  
→ cm accuracy and precision possible

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- allows for independent validation of GNSS-derived orbits

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## SLR to LEO satellites

- allows for independent validation of GNSS-derived orbits
- allows to measure orbit errors not only in radial, but also in lateral directions
- can be used to calibrate SLR stations (coordinates, range and timing biases) *if* we have confidence in GNSS-derived orbits

# GPS-based POD of LEO satellites

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- Bernese GNSS Software v5.3
- State-of-the-art models
  - Macro models for non-gravitational forces
  - In-flight calibrated GPS antenna phase patterns
  - Spacecraft parameters (attitude, CoM, sensor locations, etc.)
- Carrier phase ambiguity fixing:
  - Single-receiver ambiguity resolution using GPS products of Center for Orbit Determination in Europe (CODE), including new signal-specific satellite phase biases
  - Ties LEO orbit to IGSxx reference frame
  - Horizontal components benefit most, only weak constraint in vertical direction

# CODE clock and phase bias product

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Ambiguity-fixed GNSS clock corrections and phase bias products (enabling undifferenced ambiguity-resolution) of CODE available:

- Operationally generated
- IGS Final product line:
  - `ftp://ftp.aiub.unibe.ch/CODE`
  - `ftp://cddis.gsfc.nasa.gov/pub/gnss/products`
  - Starting from 1 January 2019
- MGEX product line:
  - `ftp://ftp.aiub.unibe.ch/CODE_MGEX/CODE`
  - `ftp://cddis.gsfc.nasa.gov/pub/gnss/products/mgex`
  - Starting from 1 July 2018
- See also `ftp://ftp.aiub.unibe.ch/CODE/IAR_README.TXT`

# Models used for POD

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- Earth gravity field: GOCO05S ( $120 \times 120$ )
- Solid Earth tides: IERS2010
- Pole tides: IERS2010
- Ocean pole tides: EOT11a ( $50 \times 50$ )
- Atmospheric densities/horizontal wind model: DTM2013 / HWM14
- Earth reflectivity/emissivity: CERES 2007
- Transmitting antenna PCO/PCV: igs14.atx
- Receiver antenna PCV: in-flight calibration (iterative residual stacking)



# Satellites considered



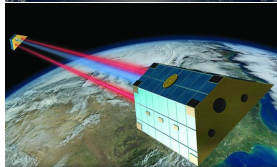
## Swarm-A/B/C:

- Magnetic field
- Launched: 22 Nov 2013
- Altitude: 460 km (A/C), 510 km (B)



## Sentinel-3A/B:

- Altimetry
- Launched: 16 Feb 2016 (A), 25 Apr 2018 (B)
- Altitude: 810 km

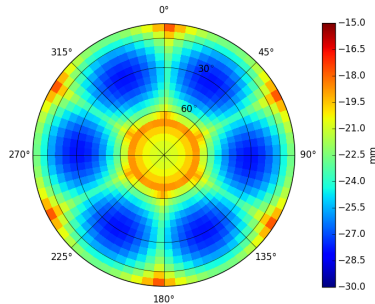


## GRACE Follow-On C/D:

- Gravity field
- Launched: 22 May 2018
- Altitude: 500 km

# Analysis of LEO SLR data

- Compute SLR residuals based on
  - known LEO satellite orbit, attitude, geometry, LRA characteristics



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  - known station locations (SLRF)

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  - state-of-the-art models (ILRS standards)

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  - outlier threshold of 20 cm, elevation cutoff of  $10^\circ$ .

# Analysis of LEO SLR data

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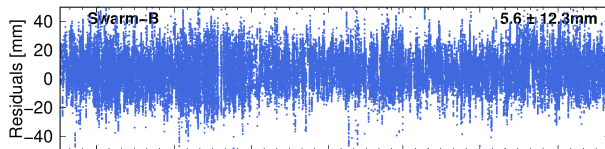
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- Compute partials of range measurements w.r.t.
  - satellite position (in RTN or s/c body frame)
  - station position (in NEU frame)
  - SLR range and timing bias

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- Compute partials of range measurements w.r.t.
  - satellite position (in RTN or s/c body frame)
  - station position (in NEU frame)
  - SLR range and timing bias
- From partials and residuals, form/solve normal equations
  - Correlations (station height and radial orbit component; time offset and along-track component)
  - A priori constraints or well observable set of parameters

# SLR residuals Swarm-B, (reduced-) dynamic



Amb.-float,  
no non-grav.  
modeling

SLR observations of 14 high-performance SLR stations, SLRF2014 station coordinates used, no parameters estimated.

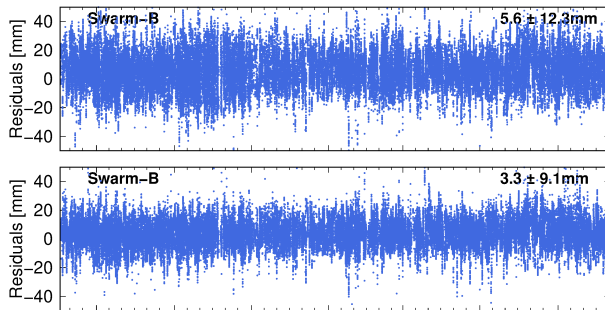
Time span: 18/154 - 19/224  
(3 Jun 2018 - 12 Aug 2019)



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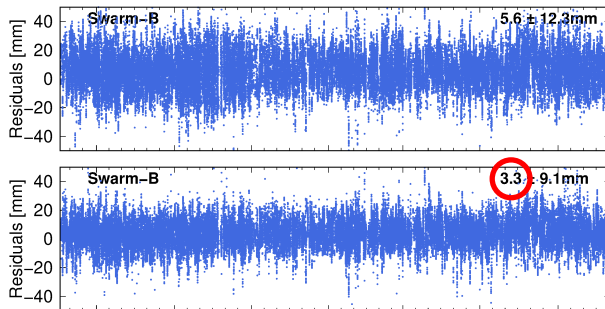
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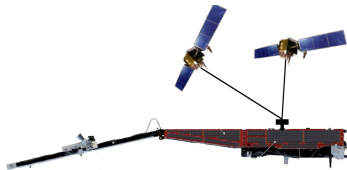
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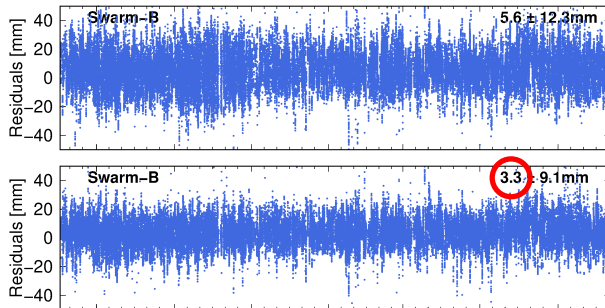
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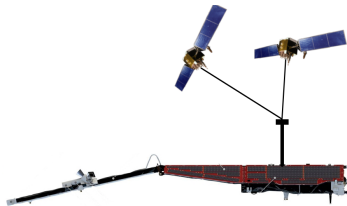
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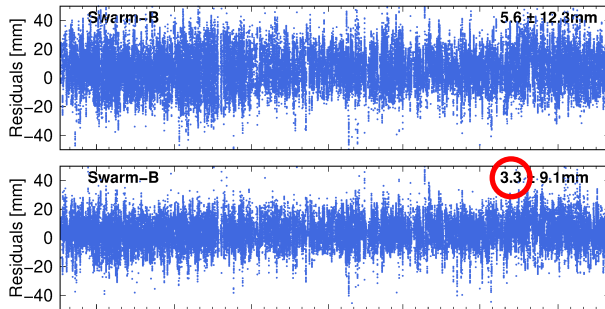
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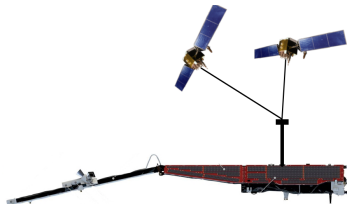
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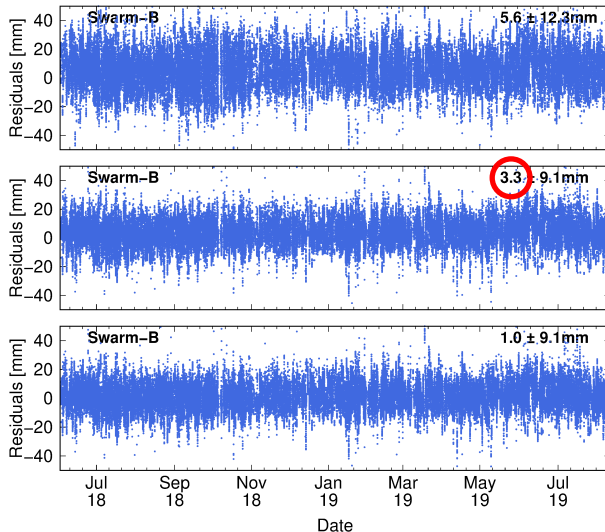
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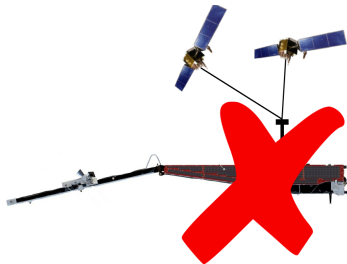


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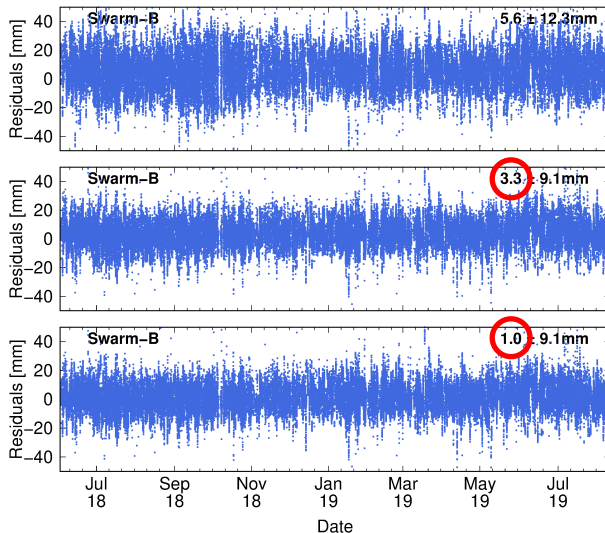
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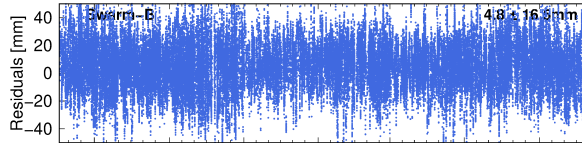
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no non-grav.  
modeling

Amb.-fixed,  
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modeling

Amb.-fixed,  
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# SLR residuals Swarm-B, kinematic

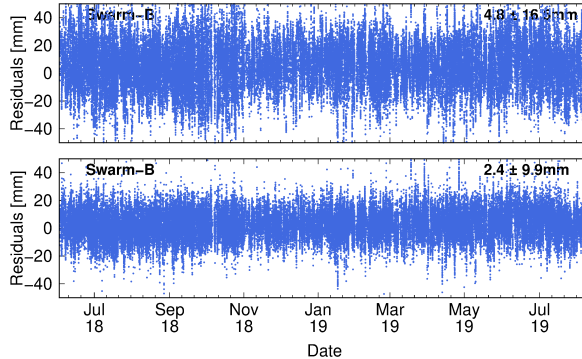
Kinematic orbits: Purely geometrically derived from GPS observations, fully independent on the force models used for dynamic LEO POD.



Amb.-float  
(16.5 mm)

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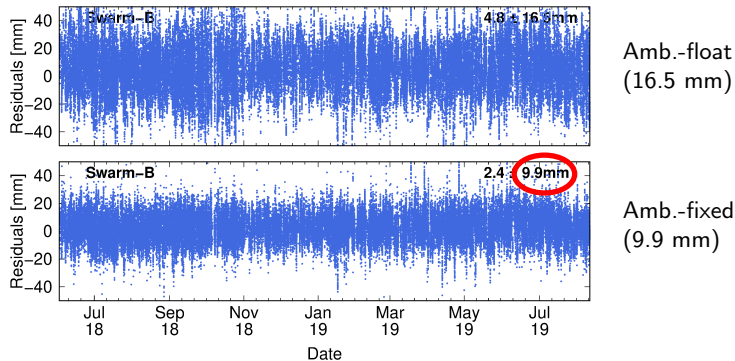
Amb.-float  
(16.5 mm)

Amb.-fixed  
(9.9 mm)



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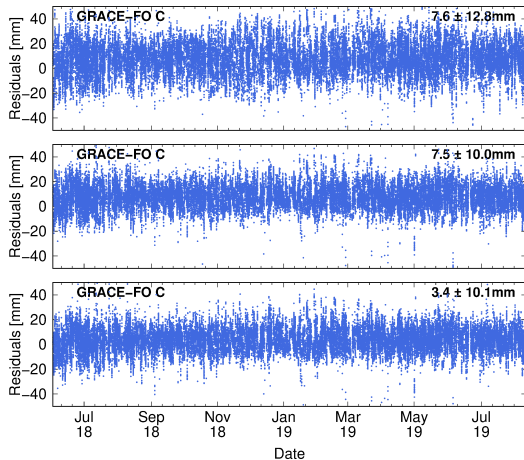
Kinematic orbits: Purely geometrically derived from GPS observations, fully independent on the force models used for dynamic LEO POD.



SLR STD comparable to ambiguity-fixed dynamic orbits (9.1 mm)!

→ limitations of SLR?

# SLR residuals GRACE-FO, (reduced-) dynamic

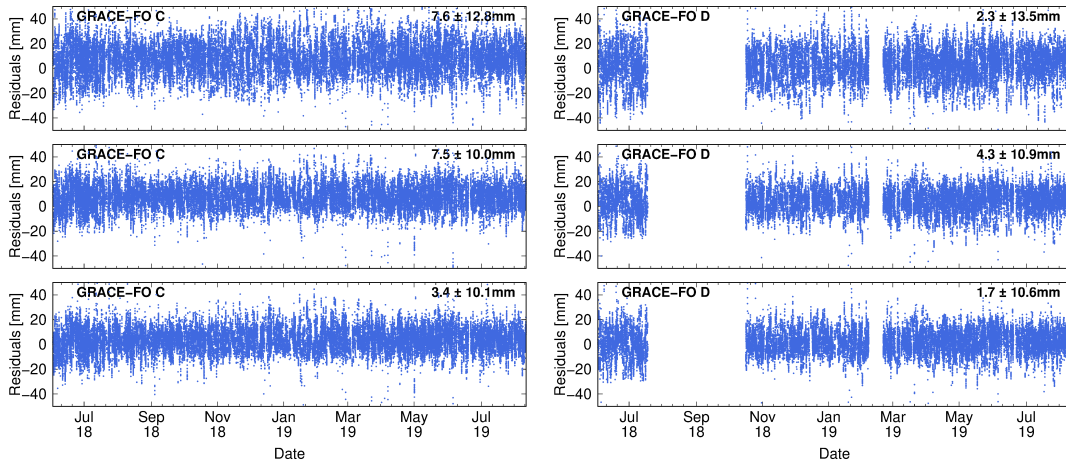


Amb.-float,  
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modeling

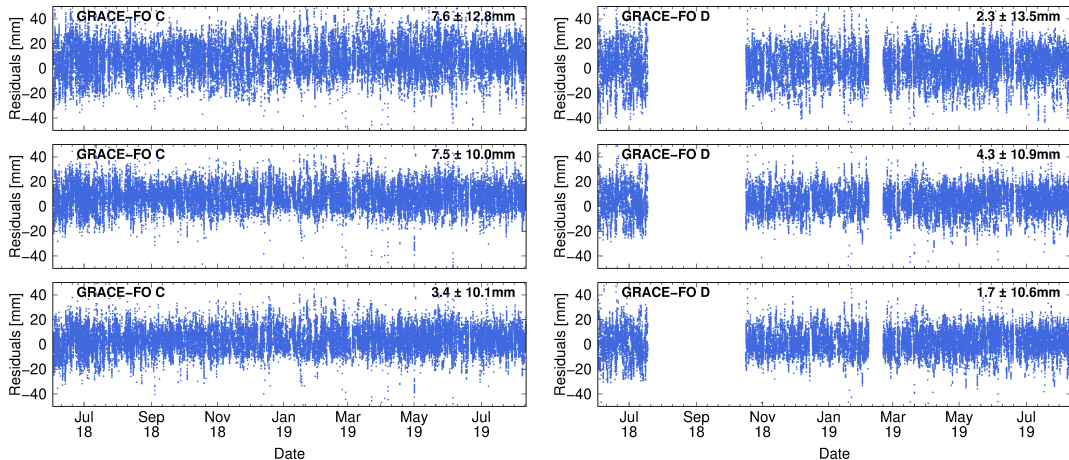
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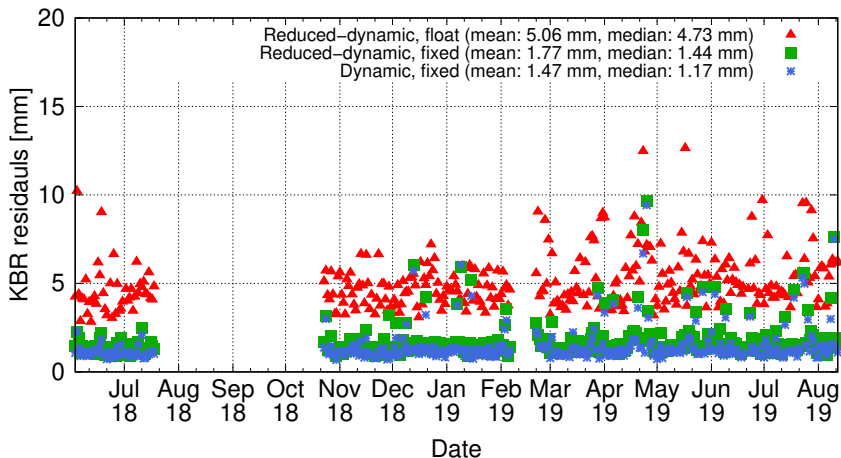
# SLR residuals GRACE-FO, (reduced-) dynamic



Noticeable offset for reduced-dynamic orbits, more pronounced for GRACE-FO C.

# K-band validation for GRACE-FO

Daily RMS values of K-band range residuals (additional independent validation):



# Estimated corrections w.r.t. SLRF2014

Coordinate and range bias corrections from 435 days of dynamic, ambiguity-fixed Swarm-A/B/C, Sentinel-3A/B and GRACE-FO C/D orbits:

Station	SOD	E [mm]	N [mm]	U [mm]	B [mm]
Badary	18900901	$8.0 \pm 0.6$	$-0.2 \pm 0.6$	$6.0 \pm 2.2$	$8.4 \pm 1.4$
Yarragadee	70900513	$4.8 \pm 0.1$	$-0.3 \pm 0.1$	$-2.5 \pm 0.4$	$0.6 \pm 0.2$
Greenbelt	71050725	$3.5 \pm 0.2$	$6.2 \pm 0.2$	$-12.7 \pm 0.6$	$-6.3 \pm 0.3$
Monument Peak	71100412	$-2.8 \pm 0.2$	$-7.5 \pm 0.2$	$-10.7 \pm 0.9$	$0.3 \pm 0.5$
Haleakala	71191402	$4.5 \pm 0.4$	$-4.5 \pm 0.4$	$1.2 \pm 1.3$	$11.0 \pm 0.8$
Papeete	71240802	$12.1 \pm 0.6$	$4.5 \pm 0.6$	$-5.1 \pm 2.1$	$-12.8 \pm 1.2$
Arequipa	74031306	$0.2 \pm 0.4$	$3.5 \pm 0.4$	$-4.1 \pm 1.4$	$8.1 \pm 0.8$
Hartebeesthoek	75010602	$-2.7 \pm 0.3$	$6.4 \pm 0.3$	$-6.6 \pm 1.0$	$4.2 \pm 0.6$
Zimmerwald	78106801	$0.8 \pm 0.2$	$2.0 \pm 0.2$	$9.6 \pm 0.6$	$7.6 \pm 0.3$
Mount Stromlo	78259001	$5.9 \pm 0.3$	$2.2 \pm 0.2$	$5.6 \pm 0.9$	$1.6 \pm 0.5$
Wettzell (SOSW)	78272201	$-1.1 \pm 0.5$	$-9.8 \pm 0.5$	$-6.4 \pm 1.7$	$5.7 \pm 1.0$
Graz	78393402	$2.8 \pm 0.2$	$3.3 \pm 0.2$	$8.7 \pm 0.7$	$11.8 \pm 0.4$
Herstmonceux	78403501	$3.2 \pm 0.3$	$1.6 \pm 0.3$	$-4.0 \pm 1.0$	$-2.3 \pm 0.6$
Potsdam	78418701	$1.0 \pm 0.3$	$3.7 \pm 0.3$	$17.0 \pm 0.9$	$-0.7 \pm 0.6$
Matera	79417701	$1.7 \pm 0.4$	$4.8 \pm 0.4$	$4.2 \pm 2.0$	$-5.3 \pm 1.0$

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# Estimated corrections w.r.t. SLRF2014 (2)

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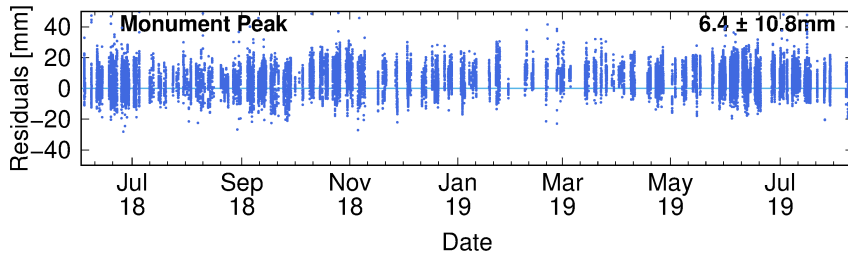
Corrections for station **Monument Peak (71100412)** from different orbit types:

Orbits	E [mm]	N [mm]	U [mm]	B [mm]
Float	$-3.3 \pm 0.2$	$-10.5 \pm 0.2$	$-21.8 \pm 0.9$	$-2.5 \pm 0.5$
Fixed	$-3.2 \pm 0.2$	$-7.8 \pm 0.2$	$-12.4 \pm 0.9$	$0.8 \pm 0.5$
Fixed + NG	$-2.8 \pm 0.2$	$-7.5 \pm 0.2$	$-10.7 \pm 0.9$	$0.3 \pm 0.5$

# Reduction of residuals (1)

Monument Peak (71100412), all satellites:

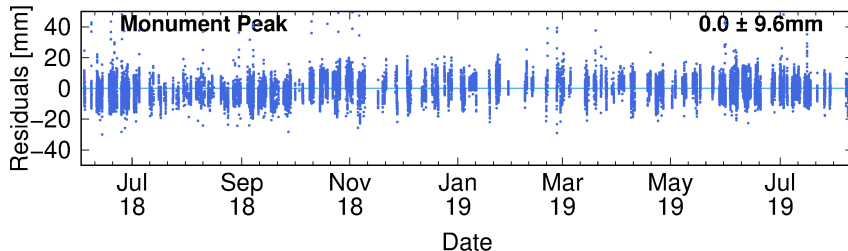
Without corrections



# Reduction of residuals (1)

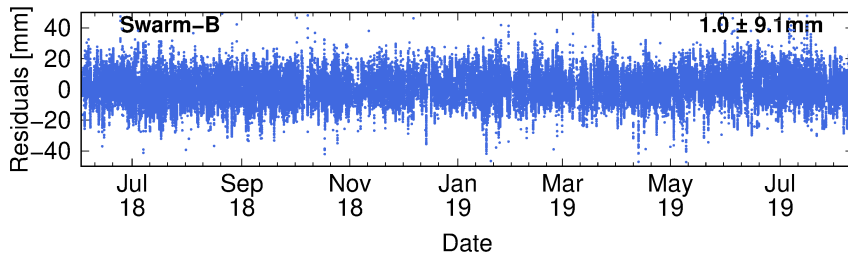
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With corrections



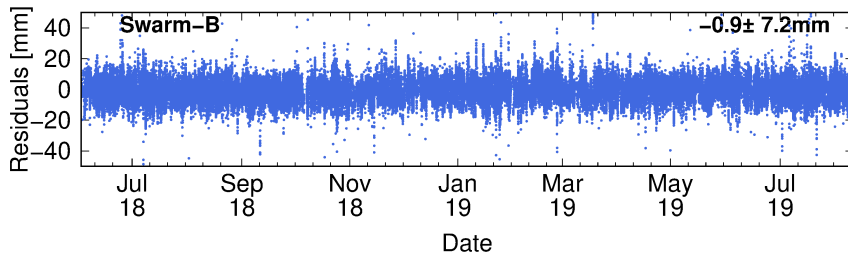
## Reduction of residuals (2)

Without corrections



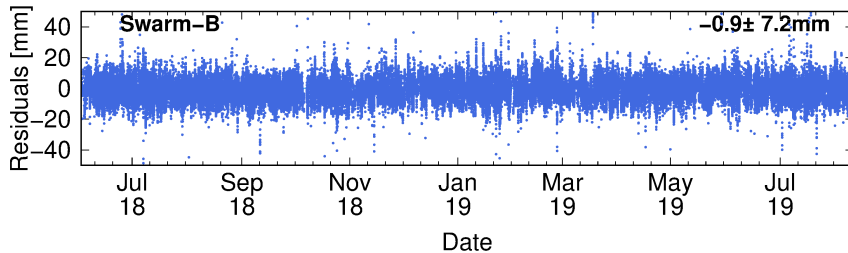
# Reduction of residuals (2)

With corrections



# Reduction of residuals (2)

With corrections



SLR residuals (mean  $\pm$  std.) of dynamic and ambiguity-fixed orbits with and without corrections:

Orbits	w/o corr.	w/ corr. [mm]
Swarm-A	$+3.1 \pm 9.6$	$+1.0 \pm 7.7$
Swarm-B	$+1.0 \pm 9.1$	$-0.9 \pm 7.2$
Swarm-C	$+2.2 \pm 9.6$	$+0.0 \pm 7.7$
Sentinel-3A	$+1.5 \pm 10.3$	$+0.0 \pm 7.8$
Sentinel-3B	$+1.1 \pm 10.2$	$-0.7 \pm 7.4$
GRACE-FO C	$+3.4 \pm 10.1$	$+1.7 \pm 7.9$
GRACE-FO D	$+1.7 \pm 10.6$	$+0.0 \pm 8.3$

# Conclusion

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- SLR to LEO satellites not only sensitive to radial, but also to 3-dimensional orbit errors, as well as **station positions and range (and timing) biases**.
- Dynamic ambiguity-fixed LEO orbits have reached a quality level that is interesting to validate/calibrate the SLR station network. Needs good knowledge of satellite geometry (antenna and reflector locations).
- Station parameter corrections sometimes at 1 cm level even for high-performance SLR stations.
- Corrections remove mean offsets in SLR residuals for individual stations and reduces standard deviation.
- Kinematic orbits profit a lot from ambiguity fixing. SLR now sees hardly any differences to the (superior) dynamic orbits.

- For methodology and further results, see  
Arnold D., Montenbruck O., Hackel S., Sosnica K.  
(2019): Satellite Laser Ranging to Low Earth Orbiters:  
Orbit and Network Validation, Journal of Geodesy,  
93(11), 2315-2334, doi:10.1007/s00190-018-1140-4
- For CODE's phase bias products, see  
[ftp://ftp.aiub.unibe.ch/CODE/IAR\\_README.TXT](ftp://ftp.aiub.unibe.ch/CODE/IAR_README.TXT)



Thank you for your attention!